Simultaneous mapping of interactions between S&T knowledge bases

The case of space communications

By

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Abstract

This paper examines the knowledge structure of the field of space communications using bibliometric mapping techniques based on textual analysis. A new approach with the aiming of visualizing simultaneously the configuration of its scientific and technological knowledge bases is presented. The bibliometric map revealed weak cognitive interactions between science and technology at the worldwide level although it brings out the systemic nature of the process of knowledge production at either side. We extended the mapping approach to the research activities of the Triad countries in order to characterize their specialization profiles and cognitive links on both sides in comparison with the structure of the field at the worldwide level. Results showed different patterns in the way the Triad countries organized their scientific and technological research activities within the field.

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Introduction

Maps of knowledge bases in a context of " potential systemic effects"

Knowledge bases (KBs) are in essence divided and dispersed (Machlup, 1984; Foray, 1999). The division of KBs is essentially due to the growth of the division of labor between institutions either public or private into the process of knowledge generation. Indeed, the increasing intensification in knowledge activities in the domain of R&D leads towards the growing of specialized institutions (OCDE, 1996). On the other hand, the dispersion of knowledge mainly stems from the cognitive limits of agents in the process of knowledge generation. The division and dispersion of knowledge constitute a source of inefficiency since KBs are often complementary even though they may be heterogeneous (Brusino & Geuna, 2001)[2]. Hence, the value of positive externalities resulting from to the public character of knowledge (David & Foray, 1995) can be raised from their assembling or recombination (Foray, op. cit.). Investigation of these complementarities is essential insofar as the existence of "systemic effects" can lead to the reinforcements of KBs in addition to endogenous cumulative effects (Price, 1963, Scotchmer, 1991) or even to the creation of new avenues (Kodama, 1992). It should however be stress that these so-called "systemic effects" are only "potential" ones because they may not be effective. Indeed, whether knowledge is a public good this does not mean that it is available to all at no cost because the value of positive externalities may be limited by its tacit character (David & Foray, op. cit.) and by the costs required for its access and transmission (Callon, 1999). These phenomena can reduce the opportunity of assembling divided and dispersed knowledge bases in spite of probable complementarities. Be that as it may, developing methods to identify these "potential systemic effects" remains once crucial and complex because of the huge amount of information on scientific and technological activities. To that end, bibliometric maps by means of co-word analysis (as well as co-classification) offer a power tool to visualize the cognitive structure of knowledge bases and their interrelations (Callon et al., 1983; Engelsman & Van Raan, 1991; Van Raan & Van Der Velde, 1992; Tijssen, 1992; Noyons & Van Raan, 1994; Grupp, 1996; Noyons, 1999) [3].

Exploring the science and technology linkages

In this perspective, exploring the cognitive links between science and technology[4] is as essential as scrutinizing the cognitive relations amongst scientific or technological KBs. Indeed, the contribution of scientific knowledge to technological developments has been stressed in many fields thanks to econometric works (Jaffe, 1989; Mansfield, 1991, 1995; Griliches, 1995), bibliometric studies (Narin & Noma, 1985; Narin & Olivatro, 1988; Narin et al., 1997) or monographic case studies (Trajtenberg, 1990). Reciprocally, technological knowledge may influence the rate and the direction of the production of scientific knowledge by providing it with new questions. In fact technological developments are still slow and costly in many high-tech industries because scientific knowledge has not yet afforded it the good answers for these issues (Rosenberg, 1991). Consequently, systemic exploration of the cognitive relations between science and technology is quintessential to characterize exhaustively the internal structure of research fields. Nevertheless, the mobilization of mapping techniques to underline this kind of linkages has been somewhat incomplete and ambiguous. It has effectively been suggested that such relations should be characterized by means of the identification of comparable cognitive structures in maps constructed at either side on the basis of the same definition (Van Raan & Van Der Velde, op. cit.; Noyons & Van Raan, op. cit.; Tijssen & Korevaar, 1997). This has been proposed in particular to overcome

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[2] as shown today by the increasing importance of interdisciplinary

[3] As Tijssen (1992, p. 30) quotes "well-known philosophers of science used maps as a metaphor for scientific theories; Polanyi (1958, p. 4) states 'all theory may be regarded as a kind of map extended over space and time', while Kuhn (1970, p. 109) notes 'And science nature is too complex and varied to be explored at random, that map is as essential as observation and experiment to science's continuing development'."

[4] Only do we explicitly mention here the interrelations between the scientific and technological knowledge bases but do not refer to other types of relations between the realm of science and the realm of technology. See for more information Brooks (1994) and Salter and Martin (2001)

the various limits of the indicator based on the counting of non patent literature (NPL) references contained in patent documents (Carpenter et al., 1980; Narin & Olivastro, op. cit.; Grupp & Schmoch, 1992) as a measure of the science relatedness of technology[5]. But the use of two different maps to explore science and technology linkages leads towards some complications at the time of the interpretation of the results. Indeed the existence of comparable knowledge structures at either side does not necessarily imply strong cognitive S&T relations. In fact the content of knowledge may to some extent differ from one side to another even though the processes of knowledge production highlight similar features (e.g. association of comparable clusters on both sides). Therefore, the difficulties mainly stem here from the meaning of "cognition" since it can be defined either at the knowledge level (e.g. language, mathematics, physics, etc.) or at the individual level, i.e. the learning process (e.g. association, information processing, etc.). So whether the maps highlight related cognitive structures at either side this suggests the existence of strong S&T linkages at the individual level rather than at the knowledge level.

In order to come against these complications and to obtain an exhaustive figure of the overall cognitive (defined henceforth at the knowledge level) structure of research fields, this paper proposes a "simultaneous mapping" approach of their S&T KBs by means of textual analysis based on patent and paper data. Such approach is applied by way of an example to the field of space communications. The methodology and data used for that purpose are described in the next section. Then we discuss the results of the "simultaneous map" at two levels: i) the worldwide cognitive structure of the field through the identification of the cognitive interactions between its S&T KBs; ii) the cognitive organization of the S&T activities of the Triad countries in comparison with the latter.

[5] About the limits of this indicator see among others Noyons and Van Raan (1994) and Meyer (2000)

Data and Method

Delimitations of space communications

First of all, a common definition of space communications for both the scientific and technology activities was chosen. This was effectively required to represent the cognitive relations between the scientific and technological KBs at the levels of sub-fields and countries. Hence, a list of ten priority R&D themes related to space communications was defined thanks to U.S. National Research Council (NRC, 1994, 1998) and Institute for Defense Analysis (IDA, 1996) reports. These priority R&D themes are: high-dielectric constant patch antennas ; high-frequency (> Ka Band) antennas ; phased-array antennas ; multi-beam antennas ; on-board satellite transponders ; multiple access ; ka band power module ; optical frequency (laser) communication systems for space-to-space links ; radio frequency space-to-space links for complex spacecraft constellations ; and lastly space solid-sate amplifiers.

The space communications database

The definition of each priority R&D theme was translated into bibliographic search equations thanks to technical experts from the European Patent Office (EPO). Each equation comprised a set of significant keywords and/or indexing codes. This step was a requisite to select properly the relevant data on European patent applications (either direct EPO applications or Euro-PCT applications) and scientific publications (reports, articles, book reviews, conference proceedings, etc.) at the world level. The identification and extraction of European patent applications were performed through EPAT and WPIL databases while scientific publications were first obtained from INSPEC and COMPENDEX databases. The time period 1990-1998 (publication years) was chosen as the reference period for the identification process. Next, COMPENDEX and INSPEC data were matched at CWTS[6] with data from all ISI files (SCI, CompuMath, etc.). This implied the exclusion of all non-articles data (e.g. books, reports, etc.)

and data from non-ISI journals. In doing this, the most relevant articles related to space communications were identified in ISI files since the process was completed at the level of individual scientific papers. Moreover, this method enabled us to include in our space communications database a large coverage of information from these three databases, especially for further bibliometric analysis[7]. At the same time, the extracted patent applications were linked to the references contained in OST patent database[8]. As a consequence, duplications between (direct) EPO applications and Euro-PCT applications were avoided as well as applications from non-legal entities. The results of these matching processes are shown in Table 1.

(Table 1 about here)

Simultaneous bibliometric mapping techniques

Once the space communications database created, a textual analysis (Lebart & Salem, 1994) was completed on the abstracts of the selected patent applications and scientific articles at the world level. In this context, abstracts were automatically scanned by means of lexical software that extracted a first list of “single-words” used in the corpus. Tool-words (e.g. the, a, or, etc.) were removed from this list since they would have been too general to be relevant to map the internal structure of the field adequately. This list constituted the input for the creation of a set of “multi words” which consist of series of at least two consecutive “single words” (e.g. patch-antennas, space-communications, etc.) in the corpus. These “multi words” were cleaned (singular/plural), unified (synonyms) and classified according to their frequencies. The most common “multi words” appearing at the top of the list (e.g. satellite-communication, space-communication) were deleted insofar as they would have been too obvious to properly characterize the internal structure of the field. The same goes for non-technical “multi-words”.

[6] Centre for Science and Technology Studies (The Netherlands)
[7] See Tijssen and van Wijk (1998) for a detailed description of this method and the three databases
[8] Observatoire des Sciences et des Techniques (France)

Lastly, a frequency threshold of five was selected in order to avoid considering irrelevant "multi words" because of their very weak frequencies.

The ultimate list of "multi words" was used to build up a frequency table. This table was constructed in order to map the cognitive relationships between S&T KBs within the field thanks to specific multivariate techniques: correspondence analysis and ascendant hierarchical clustering (Lebart et al., 1997). The frequency table (k, n+p) displayed in line all the "multi words" (k lines) and in row all the scientific and technological dimensions of sub-fields (n rows) and Triad countries (p rows). Each sub-field had indeed been split up in the table in two dimensions: one for the science side (related papers) and one for the technology side (related patents). We did likewise for Triad countries since each patent and paper had also been linked to at least one of them[9]. In other words, the initial number of modalities associated with the variable "sub-field" (i.e. n/2) and the variable "country" (i.e. p/2) had been doubled for the purpose of our "simultaneous map". As a result, the cell (i, j) in the sub-table (k, n) (res. sub-table (k, p)) indicated the number of times the "multi word" i was used in all the documents (patents or papers) related to the modality j of the variable "sub-field" (res. "country").

Afterwards variables "sub-field" and "country" were respectively selected as "active" and "illustrative" variables (Lebart et al., 1997). The use of such distinction enabled us to map simultaneously by means of correspondence analysis the links amongst the S&T KBs of the sub-fields at the world on one hand and the S&T KBs of the Triad countries on the other hand. Thus, the variable "country" did not take part in the construction of factor axis and consequently in the projection phase of n-dots. All in all, an ascendant hierarchical cluster analysis was performed to retain as much as possible of the information embedded in the table and ultimately to make easier the interpretation of distances (Van Raan and Van Der Velde,

[9] It should be not that all EU-15 countries except France, Great Britain, Italy and Germany were grouped and named "Small European Countries" (SEC) because the number of their patents and papers was too small in the field.

op. cit.). It is well worth nothing that distances between dots are indeed visualized only through two dimensions so much so that the positioning of n-dots and p-dots may be distorted here. For this reason, the cluster analysis was carried out on the first ten factor coordinates of n-dots and p-dots. Height clusters were obtained. They are shown on the map (Figure 1.) by means of dotted lines.

(Figure 1 about here)

Results and Discussion

Interpretation

Before discussing the results, few comments on how to interpret the map are helpful. Figure 1 presents the overall structure of the field of space communications over the period 1990-1998. N-dots (circles) represent the KBs of the sub-fields and p-dots (squares) the KBs of theTriad countries. The science side of the field (for both the sub-field and the country levels) is symbolized with black color while its technology side is characterized by gray color. The interpretation of distances between dots is relatively straightforward. If two dots (i.e. KBs) belong to a same cluster, then it implies that their lexical profiles described by means “multi-words” are rather similar and sub-consequently that they maintain close cognitive relations. Hence, the expansion of both these KBs may lean on high reciprocal externalities and “systemic effects”. Therefore, the more a cluster contains various KBs, the higher the potential value of positive externalities is.

Links between knowledge bases at the level of sub-fields

A first examination of the S&T structure of the field brings out a weak cognitive interconnection between the realm of science and the realm of technology. The relations between science and technology are effectively almost non-existent. An exception concerns the sub-field "optical frequency communications" whose S&T KBs belong to a same cluster (cluster 5). It is also interesting to observe that the technological KB of "amplifier" is close to the scientific KBs of "multiple access" and "transponders" insofar as they are linked with cluster 8. This entails a certain degree of "trans-disciplinary" between S&T KBs. One might justifiably suppose that the weak cognitive relations between science and technology stem from the single reference period (1990-1998) considered at the time of the extraction of both patent applications and scientific papers. In fact a temporal gap between scientific progress and technological developments usually characterizes the generation of knowledge in many fields. Thus, technological developments over the last decade might have benefited from the scientific knowledge produced before that period. However, its substance is not considered here. In other respect, these weak cognitive linkages may also derive from an "institutional constraint" rather than an "technological constraint". A strict division of labor between public research institutions and the industry in the production of new S&T knowledge may indeed explain this weak interface. But we showed earlier that this hypothesis did not totally seem exact because the industry sector in the United-States, Europe and Japan had been very active in the production of scientific knowledge over that period within the field of space communications[10] even though public/private interactions were non-intensive (Hassan, 2001). In fact, most of the links between sub-fields does not rest on scientific and technological interactions. They are definitively limited to either side.

On the technology side, KBs are mainly grouped together in clusters 3 and 5. Cluster 3 binds the technological KBs of "HF antennas", "patch antennas", "multibeam antennas" and "phased-array antennas". Cluster 5 covers the technological KBs of "radio-frequency space-to-space links", "transponders", "multiple access" and "optical frequency communications" but also its scientific KB. The existence of these two main technology-based clusters emphasizes

[10] In the United-States, 34.7% of the scientific production is due to the industry; in Europe 21.1%; in Japan, 46.2%.

the crucial importance of the potential benefits of combining these different KBs to generate new technological knowledge in each sub-field. In fact, only is the process of knowledge production related to “power modules” (cluster 6) characterized by its isolation at the technological side. The same goes on the science side. Most scientific KBs are divided into two large clusters (2 and 8). Only are the scientific KBs of “amplifiers”, “power modules”, “optical frequency communications” and “radio frequency space-to-space links” excluded from these main science-based clusters. Cluster 2 links the scientific KBs of “HF antennas”, “patch antennas”, “multibeam antennas” and “phased-array antennas”. Cluster 8 associates the scientific KBs of “transponders” and “multiple access” but also the technological KB of “amplifiers”. Hence, the internal structure of cluster 2 is mostly similar to the structure of the technology-based cluster 3 because both of them are built upon the same sub-fields. In other words, the process of knowledge production has comparable potential systemic characteristics in both clusters. Following a same reasoning, the science-based cluster 8 and the technology-based cluster 5 have a similar nucleus: “transponders” and “multiple access”. Nevertheless, the “potential systemic effects” remain rather different in these clusters because of their dissimilar overall structures. Finally, three “single” clusters can be observed: cluster 4, cluster 7 and cluster 1. Cluster 4 envelops scientific research activities on “power modules”. So the production of knowledge within this sub-field does not seem to be able to benefit from “systemic effects” on either side. Cluster 7 includes the scientific KB of “radio frequency space-to-space links” while the sub-filed is connected to other ones at the technology side as we have seen. More unpredicted and already quoted is the situation of cluster 1 which only encompasses the scientific side of “amplifiers” while its technological KB is oddly linked with the large science-based cluster 8. The existence of these three single clusters leads one to believe that “potential systemic effects” are slightly inferior at the science side than at the technology side.

Links between knowledge bases at the level of countries

The prior developments attempt to analyze the cognitive relations between S&T KBs at the sub-field level by means of the worldwide knowledge production within the field of space communications. We now discuss the S&T positioning of the Triad countries in comparison with clusters. To begin with their technological activities, it appears that they are essentially focalized on clusters 3 and 5 (Figure 1.). However, it should stress that Germany is the only country that principally carried out technological activities within cluster 5 so that it can not participate to any form of collective production of knowledge with the other Triad countries. Their scientific research activities are more disseminated although they are mainly clamped down on the two main science-based clusters (clusters 2 and 8). France, Germany and Japan concentrate their scientific activities on cluster 2 while the United-States, Great-Britain, Italy and the Small European Countries (SEC) deploy theirs in the bounds of cluster 8. In this perspective, the examination of the positioning of each Triad country at either side is interesting. On one hand, only France and Japan develop their activities on both sides in two clusters whose structures are similar but not closely linked from a cognitive point of view: cluster 5 and cluster 2. This means that the cognitive S&T interface for the Triad countries is weak either at the knowledge or the individual level. On the other hand, the United-States, Great-Britain, Italy and the SEC produce scientific knowledge in sub-fields (cluster 8) within which the generation of technological knowledge seems quasi non-existent at the Triad level. Therefore, one may suppose that two different strategies are pursued in the Triad, namely the production of scientific knowledge either to reinforce existing technological KBs (France, Japan) or to create new ones (United-States, Great-Britain, Italy, SEC). According to this assumption, the S&T positioning of Germany looks surprising. Indeed, it produces technological knowledge in sub-fields that have not been prospected by the other Triad countries. But it unexpectedly focuses its scientific activities in sub-fields that have already largely been explored from a technological point of view. It is to be wondered why Germany does not concentrate its scientific efforts on cluster 8 so that to improve the efficiency of its allocation of resources devoted to its technological activities carried out in cluster 5 insofar as they are probably highly uncertain. Its scientific activities could indeed increase its probability to produce relevant technological knowledge since they could provide useful information for further investment in the process of exploration/exploitation[11].

The examination of the S&T specialization profiles of these countries enables us to underscore the existence of networks of production and distribution at either side within the Triad. In this perspective, it should be note that these networks are “virtual” insofar as they entirely lean on the likeness of their S&T cognitive profiles. This means that the S&T knowledge flows between countries within such networks remain potential in the same way as the previous so-called “systemic effects”[12]. According to these interpretations, it comes out that all the Triad countries expected Germany form a “virtual network” on the technology side because their KBs are closely linked together. Therefore, significant potential technological knowledge flows amongst the Triad countries characterize the field. Nevertheless these knowledge flows are not diversified because of the localization of their technological activities on cluster 3. Conversely, two different “virtual networks” emerge on the science side due to a higher cognitive division of labor among the Triad countries in the process of knowledge creation. They group together on one hand France, Germany and Japan and on the other hand the United-States, Great-Britain, Italy and the SEC. As a result, the potential impact of positive externalities and sub-consequently the potential scientific knowledge flows at the level of the Triad countries are more limited on this side. However, these lower cognitive relations between the Triad countries on the science side allow the production of more diverse knowledge that can lead towards a better allocation of resources at the technology side due owing to a diminution of the uncertainty.

[11] See David et al. (1992)
[12] Jaffe (1986) was among the first to develop this idea of potential knowledge flows between actors based on the likeness of their R&D profiles

Conclusions

The simultaneous mapping approach developed in this paper allowed us to investigate deeply the overall cognitive structure of space communications at the worldwide level and also the organization of the S&T activities at the country level within the Triad over the last decade. We first found that weak cognitive interactions between science and technology characterized the field of space communications in spite of related processes of knowledge generation on both sides. Indeed, the map revealed significant “potential systemic effects” and above all similar associations between sub-fields (e.g. amongst the antenna-based sub-fields, “transponders” and “multiple access”) at either side but hardly any links between their scientific and technological KBs. This confirms in a way that a similar cognitive structure at the science as well as at the technology side does not necessarily imply the existence of cognitive links between scientific and technological developments as a general rule but comparable learning processes.

In other respect, the identification of the specialization profiles of the Triad countries allowed us to characterize different patterns in the way they organized their S&T activities within the field. We found that all the Triad countries except Germany were essentially focalized on the antenna-based fields at the technology side while the other sub-fields were relatively discarded over the last decade. Nevertheless the map revealed a different situation at the science side insofar as their activities were more distributed among sub-fields. In deed, some Triad countries explored sub-fields on the science side that were hardly prospected from a technological point of view (e.g. “transponders”, “amplifiers”). These heterogeneous S&T strategies within the Triad may reflect the different goals that countries attached to scientific research, i.e. the reinforcement of existing technological KBs (France, Japan) or the creation of new ones (United-States, Great-Britain, Italy, SEC). These differences as regards the organization of S&T activities from one side to the other can have influenced the capacity of the Triad countries to take fully advantage of positive externalities. Indeed, we demonstrated that the low division of labor between countries on the technology side can have enabled them to benefit from potential knowledge because of their cognitive proximities. This was not the case on the science side due to the formation of two “virtual networks” over the last decade. Nevertheless the production of knowledge was more diversified there.

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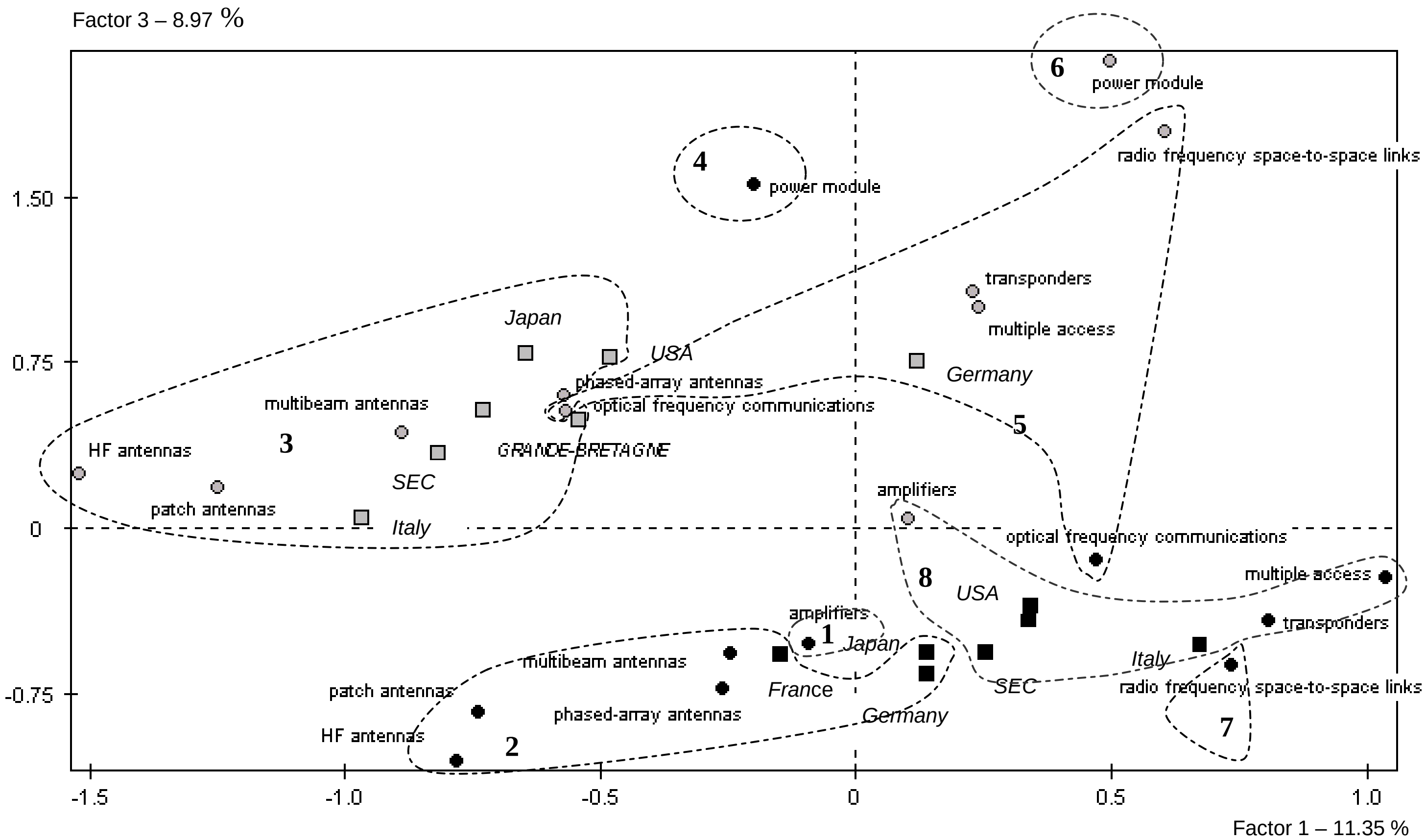
Figure 1. Cognitive structure of the field of space communications (1990-1998)



Source: Derwent, Inspec, Compendex, ISI ; *Processing :* OST, CWTS, Author; Notes: Black rings represent the science side of space communications and grey rings the technology side. Clusters generated from an ascendant hierarchical clustering drawn in the map are used to delimit the cognitive relations between actors.

Table 1. “Space communications” papers and patents (1990-1998)

	Patent applications		Scientific publications		
Priority R&D themes	**Direct EPO or Euro-PCT**	**Direct EPO or Euro-PCT (OST processing)**	**Inspec**	**Compdx**	**ISI (CWTS processing)**
Solid-state amplifiers	10	8	151	51	18
High dialectric constant patch antennas	142	70	559	297	85
High-frequency antennas	104	64	222	94	30
Ka band power module	73	37	57	54	9
Multi-beam antennas	96	50	354	162	164
Multiple access	238	121	1061	902	65
On-board satellites transponders	22	10	754	546	65
Optical-frequency (laser) communication systems for space-to-space links	38	27	445	131	52
Phased-array antennas	90	48	336	206	37
Radio frequency space-to-space links for complex spacecraft constellations	24	11	179	104	27

Source: CWTS, OST, Author